Chapter 2
Energy Storage Applications

2.1 An Introduction to Energy Storage Applications

As discussed in Chap. 1, energy storage through solid-liquid phase change is inherently a transient process and is best suited for systems that experience repeated transients, such as on-off or periodic peaking cycles, or for those systems which require thermal energy storage for later use. PCMs are commonly used in applications for both thermal management and for thermal energy storage.

Interest in PCMs for thermal management of systems can be traced back at least through the 1970s. NASA in particular was interested in the use of PCMs as what were then referred to as “thermal capacitors” and PCMs were implemented in several moon vehicles and in Skylab [1]. The 1977 NASA tech brief “A Design Handbook for Phase Change Thermal Control and Energy Storage Devices” [2] was one of the first comprehensive PCM references, and is still widely cited and used today.

During the 1970s and 1980s, interest was also building in the application of PCMs in solar systems [3–5] for thermal energy storage in both large solar plants, and in smaller domestic applications such as domestic hot water systems. The concept of embedding PCMs in various types of building materials, such as wallboard and floorboards, in order to create houses and offices with lower heating and cooling loads for greater energy efficiency, also began in the 1970s/80s [6, 7]. Simultaneously, a significant amount of fundamental research was being completed on PCMs, considering in-depth the melting and solidification processes, and the roles of conduction and natural convection on the phase change processes [8–11].

With the growth of computing power through the 1980s and 1990s, integrated circuits began dissipating significant amounts of heat and PCM applications in the thermal management of high performance, military and consumer electronics came on the scene in the late 1990s [12–14]. More recently, PCMs have seen application in textile design for energy absorbing clothing for military and consumer products [15].

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This chapter takes a look at some of these more popular applications. The use of PCM in each application is explained considering the end goal of the design and its temperature range. With approximately 45 years of PCM usage to consider, this chapter certainly is not meant to be an exhaustive review of PCM applications, but instead is meant to illustrate how and why PCMs are being implemented in each case, with the benefits of PCM implementation and also any design concerns noted in each case. When available, comprehensive reviews on each topic are cited.

2.2 Thermal Management of Electronics

The design of electronics over the past five decades has closely followed "Moore's law" in which processing power doubles approximately every 2 years. This exponential increase in processing power has been a great boon to the field of electronics, but a great challenge for thermal engineers. Particularly when combined with a significant decrease in packaging size, the heat transfer aspects of electronic packaging grow more challenging every year. For reliability reasons, most chip packages are constrained to operate below 85 °C and all the generated heat must be dissipated into the environment during both steady-state and transient operating conditions.

For standard computing systems such as laptops and desktops, the heat loads can usually be dissipated using a heat sink coupled with a fan, assuming enough space exists in the casing for the heat sink geometry. High performance computing systems with higher heat flux loads are increasingly turning to liquid based cooling systems such as cold plates, which then necessitates the use of auxiliary support equipment such as pumps, piping and external heat exchangers. But for portable electronics, one of the largest segments of the consumer electronics market, and which includes tablets and smart phones, possible thermal management solutions are severely constrained by their form factor. The demand for ultra-thin systems precludes the use of large air-cooled heat sinks or pumped liquid loops.

Fortuitously, most portable electronics are used in on/off or peaking duty cycles, which makes the use of PCMs for thermal management feasible. Many tablets and smart phones are in low-power standby mode for most of the day, with random bursts of activity that cause processing power to peak. For these applications, PCMs can be used to absorb these bursts of energy and then to dissipate the stored heat when the peaking cycle has ended. The idea is to have the heat effectively penetrate the PCM when the peaking cycle begins, melting the PCM and maintaining a constant operating temperature. The length of the PCM melt cycle should be matched to common usage time intervals (perhaps 10–30 min). Once melted, the PCM must shed its heat to the environment as it solidifies and "recharges" for the next cycle. The use of PCMs in this application is to delay the onset of steady-state conditions for as long as possible. Once the PCM is fully melted, if the electronics still remain on, the temperature will rise through sensible heating to a steady-state operating condition (See Fig. 2.1).

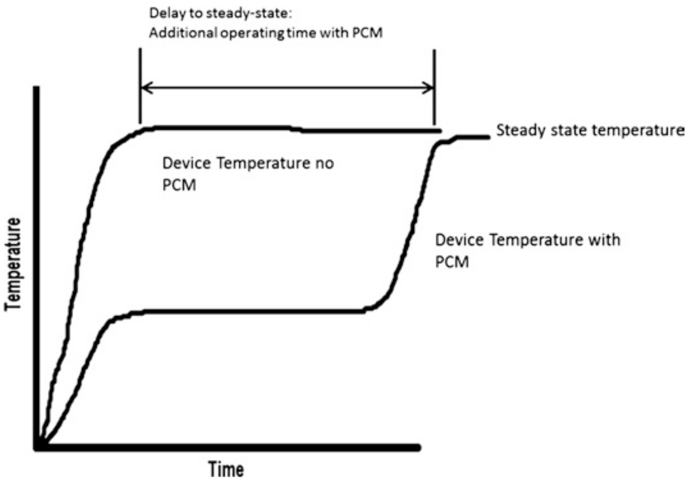


Fig. 2.1 Delay to steady-state of PCM in electronics thermal management

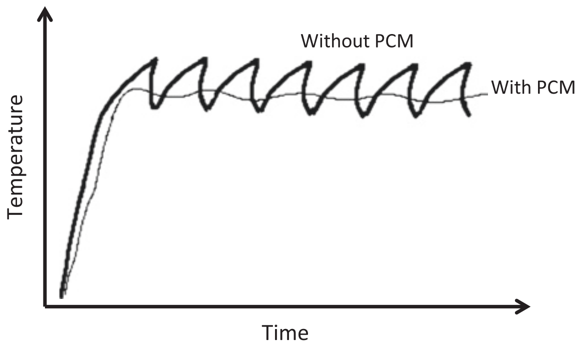


Fig. 2.2 Electronics casing temperature during peaking operation with and without PCM

The use of PCM in this way maintains a more constant temperature of the electronics in peaking operation (see Fig. 2.2), and is a passive thermal solution with no mechanical working parts like fans or pumps, thus increasing reliability. In this case the PCM is used in a thermal management application, not an energy storage solution, since the stored heat is not used productively elsewhere in the system. The PCMs used in these applications typically have melt temperatures between 36 and 56 °C in order to keep the junction temperature well below the 85 °C allowable for integrated circuits. For portable electronics, it is important not only to keep the junction temperature low, but also the casing temperature low in order to protect the user from burns. In general, casing temperature must be maintained below 40–45 °C for safe usage. PCMs based on paraffin are most commonly used in these systems although liquid metal blends are sometimes implemented.

Electronics thermal management PCM research has been ongoing since the 1990s and these types of solutions are of great interest to today's electronics manufacturers. Many companies are actively designing PCM based thermal solutions and a number of small companies have PCM based heat sinks and spreaders already on the market. By taking a brief look at some of the literature in the field, the usefulness of this technology can be seen.

The initial work in this field focused on proving that PCMs could effectively act to suppress temperature spikes and maintain consistent junction temperature in operational ranges similar to those occurring in electronic systems. For instance, in the late 1990s Pal and Joshi [13] completed a numerical study of the use of PCM for passive thermal control in electronics systems during variable power operation. They used two different PCMs, eicosene (a paraffin) and a eutectic alloy of Bi/Pb/Sn/In. It was shown that both PCMs effectively controlled the system temperature. Vesligaj and Amon [14] also looked at time varying workloads on electronic systems, both experimentally and numerically. The duty cycle in this case was an initial ramp up of 45 min at 10 W of power, followed by 30 min off and 15 min on in repetitive cycles. It was seen that the use of PCM damped out the system temperature swings resulting from the power cycles, maintaining a casing temperature of 31 ± 1 °C compared to 37 ± 7 °C without any PCM, for a significant overall temperature and temperature swing reduction.

The effectiveness of PCM thermal management as compared to copper heat spreaders was illustrated by Krishnan et al. [16] who performed a theoretical analysis which compared the thermal performance of different PCMs to that of a conventional copper heat sink. The analysis considered the effects of conduction and phase change through the different materials when subjected to large heat loads of between 300 and 600 W. The PCMs considered included triacontane (melt temperature = 65 °C), aluminum foam impregnated with triacontane, and two metallic PCMs—a Bi/Pb/Sn/In alloy and a Bi/In/Sn alloy which have melt temperatures of 57 and 60 °C respectively. It was found that that the PCMs were significantly better at controlling the junction temperature (10–20 °C cooler) than the traditional copper heat sink and consistently extended the time to achieve steady state. This work noted the need to enhance the thermal conductivity of most organic PCMs for effective operation, which was done in this case with aluminum foam. This option will be discussed in depth in Chaps. 3 and 4.

These works, and others, fully established the potential impact of PCMS in the thermal management of electronics. As such, many researchers have studied the direct implementation of PCM in electronics applications. The feasibility of using a PCM for transient thermal management of a cellular phone was investigated by Hodes et al. [17]. In this project, the transient response of a mock handheld phone was determined using two types of PCM: tricosane, a common paraffin wax with a melt temperature of 48 °C, and Thermasorb-122, a commercially available PCM encapsulated in a pellet-like plastic shell with a melt temperature of 50 °C. It was determined that for low power loads even small masses of PCM can substantially increase the operational time for a handheld phone before overheat occurs. For a heat load of 3 W, the presence of the PCM doubled the overall usage time of the device before the casing reached the peak operational temperature. In most portable electronics, the casing temperature limit is reached long before the junction temperature limit.

A similar study [18] looked at a slightly larger system (97 mm by 72 mm by 21 mm) which is certainly too thick to mimic today's smart phones, but does provide some insight nonetheless. Four different plate fin heat sinks were designed for the system. Three of these featured a varying numbers of fins with n-eicosane with a melt temperature of 36.5 °C filling the space between the fins. The fourth was a standard air cooled heat sink. The heat sinks were subjected to different duty cycles of 3–5 W as follows: Light usage (On for 5 min, Off for 50 min, On for 5 min), Moderate usage (On for 15 min, Off for 30 min, On for 15 min) and heavy usage (On for 25 min, Off for 10 min, On for 25 min, Off for 10 min). Without the PCM, the casing temperature quickly exceeded its temperature limit of 45 °C while the PCM filled heat sinks featured greater operational times and lower device temperatures. The heat sinks the greatest number of fins exhibited the lowest device temperatures. This was because the fins provided a direct path for heat penetration into the PCM mass pointing to the benefits of enhancing the thermal conductivity of paraffin PCMs.

The results of this test also showed that it takes significantly longer to solidify the PCM than to melt it, indicating the recharge time is a limiting factor in many applications. This is due to the conduction-dominated nature of the solidification process as compared to the natural convection-dominated nature of the melt process. As the PCM melts, it exhibits density differences which induce natural convection enhancing the melt process and speeding its progression. The low thermal conductivity of the PCM and the slower nature of the conduction-dominated freezing process can potentially lead to long recharge times which must be considered during the design process.

For today's thin form factor electronics, the use of PCMs embedded in heat spreaders may be an effective solution. The use of very thin layers of PCM minimizes the solidification time while also meeting geometric constraints. For example, a PCM based heat spreader was fabricated from electro-deposition of metal over a template of spherical microcapsules (<100 μm in diameter) containing PCMs [19]. The authors refer to this as a microporous metal matrix (MMM)-PCM composites. The paraffin used in this application was SunTech P116 with a melt temperature of 47 °C and the deposited metals were copper and aluminum. The resulting heat spreader can be very thin depending on how many layers of PCM microcapsules are used. A COMSOL simulation of this design indicated that that it was effective at maintaining the device casing temperature under the temperature limits and that the temperature of the MMM-PCM composite heat spreader after 25 min was 30 °C below the temperature of a comparable copper heat spreader.

Of course portable electronics are not the only type of electronics that work within peaking or on/off duty cycles. In fact many power electronics systems also work this way. Electronics power supplies are also beginning to draw attention as potential PCM thermal management applications, particularly energy–dense Li-ion battery packs. Li-ion packs, such as those used in hybrid vehicles generate heat during their discharge cycle, yet the lifespan of the battery pack is highly dependent on maintaining a consistent operating temperature. In one study [20], composite blends of paraffin and expanded graphite paraffin with different phase change temperatures (36, 44 and 52 °C), packing density and mass percentage of paraffin were analyzed for the effective thermal control of four simulated battery packs. It was found that the PCM composites effectively maintained a consistent battery pack operating temperature avoiding overheat.

From this overview it can be seen that PCMs have been shown to be an effective solution for the transient thermal management of different types of electronic systems. The primary advantages to using PCMs in these applications are increased reliability due to the passive nature of the melt/solidification process and the suitability for low form factor systems. The main challenge to their greater implementation is the low thermal conductivity that many PCMs with melt temperatures in this range exhibit, although as shown, there are ways to mitigate the impact.

2.3 Energy Storage in Building Materials

Energy storage has long been a part of the selection of building materials. From the earliest days, man has wanted to design comfortable dwellings that absorb heat during the day, preventing overheating, and which retain as much heat as possible at night, maintaining a comfortable temperature within. The use of material such as adobe is a prime example. These materials store significant amounts of sensible heat during the day, and release it slowly during the cooler night hours creating a comfortable abode in desert environments. Adobe housing has been popular for millennia, and among the most famous adobe dwellings is Cliff Palace, in Mesa Verde National Park in Colorado (see Fig. 2.3). Adobe houses are still a popular option in the American Southwest today.

Fig. 2.3 Mesa Verde's Cliff Palace sandstone and adobe dwelling

The interest in PCMs in building materials is in the ability to harness energy storage through the latent heat phase transition instead of through sensible heating. The primary benefit to this in building materials is the higher energy density available when storing energy through phase transition, meaning that more energy can be stored in a constant volume. By storing energy through the phase transition, the overall HVAC load of the structure can be reduced. This is related to the constant temperature of the phase transition. When solar energy is incident on sensible energy storage materials, the temperature of the materials rises. For buildings this means that in warm weather months the HVAC system is needed to maintain comfortable temperatures within. However, with PCM-based building materials, the temperature will only rise until the point of phase transition is reached. At that point, continued incident energy is absorbed through the latent heat of fusion, and the temperature remains constant. If this can be matched to the building comfort set point, HVAC loading can be significantly reduced. This works particularly well as noted in the high desert environments where it can be hot with high solar insolation during the day and yet also have cool nights during which the heat is released from the PCM.

Not surprisingly then, the main areas of emphasis for PCM implementation for energy storage in building systems are in PCM-based gypsum board. In most of these systems, the PCM transitions from solid to liquid in the range of 20–30 °C. The method of containment of the PCM in the gypsum board varies from design to design, and a few of these applications are highlighted here. Currently there are several commercial PCM gypsum boards available, many of which use an encapsulated PCM supplied by BASF which melts at 23 °C.

There are many research teams which have studied the use of PCMs in wallboard to quantify its effectiveness. For instance, in an early paper by Feldman et al. [21], PCM based on methyl palmitate with a melt range of 23–26 °C and a latent heat of 180 kJ/kg was impregnated at 25 wt% into a standard gypsum wallboard by direct immersion of the wallboard in the liquid PCM. For this material, the surface tension was such the liquid PCM wicked into the pores in the wallboard, and upon repeated melt/freeze cycles, the molten liquid PCM was effectively constrained via capillary forces within the wallboard without any seepage of PCM. Thermal property testing of the composite material showed that over a 3.5 °C interval the total storage capacity was about twelve times higher than the storage capacity of wallboard alone, showing a significant increase in energy density.

Full-scale room testing was done by Athienitis et al. [22]. In this study, a gypsum board with 25 wt% PCM was again made using direct immersion of wall board in liquid PCM, in this case butyl stearate with a phase change transition between 16–21 °C. The PCM wallboard was installed in an existing room test bed 2.82 m wide by 2.22 m long and 2.24 m tall. The experiments were run under simulated winter conditions with the outdoor ambient set as cold as −25 °C, and the indoor air temperature set at 23 °C from 6:00 a.m. to 5:00 and to 16 °C outside of those hours. The room had a single window (1.08 m^2) which allowed for insolation. Previous testing with this same test bed under sunny day conditions had shown that the room temperature could reach 30 °C, while under the exact same conditions the PCM-based wall board passively controlled the temperature of the room to 26 °C. During the discharge cycle at night, the surface temperature of the PCM gypsum board was 1–1.5 °C higher than the standard wallboard, clearing showing direct energy savings both during the day and at night.

Some more recent studies, such as Zhang et al. [23] have used PCM microencapsulation instead of direct immersion in liquid PCM. In microencapsulation, the PCM is contained within a microscale polymeric bead. This encapsulation removes the dependence on capillary action to contain the liquid PCM within the wallboard. Instead the PCM stays safely with the shell at all times, preventing leakage and also preventing any off-gassing during melting. In this study [23], the PCM capsules were combined with gypsum powder and glass fiber to form gypsum boards by compression molding. The PCM was octadecane with a melt range of 26–28 °C. Sample composites with ratios of PCM/Gypsum from 30/70 up to 60/40 were fabricated and tested. A single 50/50 composite gypsum board was found to absorb energy and moderate temperature rise for periods of up to 48 min, while also reaching lower final temperatures than standard gypsum board and eliminating entirely any possibility of PCM seepage. A more detailed review of the use of microencapsulated PCMs in building materials is provided by Tyagi et al. [24] and a review of PCMs of various types in building materials by Parameshwaran [25].

Of course wallboard is not the only building material into which PCMs can be dispersed for energy storage. Concrete is another such example. Han et al. [26] studied microencapsulated PCMs dispersed within cement. The microencapsulation is used in this case because liquid paraffin is extremely difficult to disperse in cement which can lead to non-uniformity throughout the composite. The microencapsulated PCM beads are much easier to disperse within the cement. The PCM used in this case is a commercially available Micronal DX technology made by BASF with a melt point of 26 °C. In this case, carbon nanotubes are also added to the cement to offset the reduction in strength and thermal conductivity that can result from the PCM addition. The composites featured 5 % PCM and 1 % CNT by weight. The composite was used to fabricate a scale-down house-sized building model, with a control model built with plain mortar as a reference. The building model fabricated from the PCM cement showed a reduction in internal temperature of almost 7 °C under outdoor test conditions.

The use of PCM in roofing materials has also been investigated. Kosny et al. [27] studied an experimental roof design which incorporated a PCM energy storage system for use with roof mounted photovoltaics (PV). The roof design was a composite made from layers (in order) of roof decking, macroencapulsated PCM, fiberglass insulation and metal panels with pre-installed PVs. The macroencapsulated PCM consisted of an organic PCM with a melt temperature range of 26–30 °C in plastic film pouches with dimensions of 4.4 × 4.4 by 1.3 cm. Traditional roofing materials (standard shingle roof) served as the experimental control. Data on the performance of the roofing systems were collected continuously over a 12 month period. Overall, the PCM roofing system was shown to offer benefits on about 2/3 of the days of the year. The effectiveness was reduced because during some winter periods the PCM remained entirely solid with no melting, and during certain summer periods the PCM remained entirely liquid with no solidification. The remainder of the time it cycled through phase change for at least some of the day. During the winter season as a whole, the PV-PCM roofing system reduced heating load by 30 %, and during the summer the average cooling load was reduced by 55 %.

It can be seen from this brief overview that PCMs have been shown to be an effective way to reduce energy costs when embedded in building materials. The PCMs can be embedded by direct immersion, macroencapsulation or microencapsulation, depending on the host material and application. The primary advantages to using PCM in building materials is their ability to store energy without temperature increase, thus mitigating temperature rise and thus HVAC loading within the building. Several commercial products are now available, and the only barrier to their greater implementation is currently cost and wide scale availability. These materials can be further refined any optimized by addressing issue of melt temperature range to avoid situations where the PCM remains either fully liquid of fully frozen for days at a time, as well as issues of weight and for concrete, structural integrity.

2.4 Solar Energy Systems

2.4.1 Concentrating Solar Power Plants

An obvious drawback of solar power systems of any type is the limitation of the effectiveness of the technology to periods of high radiant solar energy. This is particularly an issue for large commercial solar power plants, as electricity demand is not limited to daylight hours. The use of phase change materials for thermal energy storage (TES) in these applications can extend the usefulness of the technology so that benefits can be provided even where there is low or no direct insolation. In fact, for large solar power plants, fully integrated TES is necessary for the design of economically viable plants in order to reduce reliance on supplemental fossil fuel burners.

Commercial solar power plants are designed using the concept of Concentrating Solar Power (CSP). In these plants, sunlight is reflected and concentrated using mirrors and then used to heat a carrier fluid. There are four main types of concentrator designs: parabolic trough, linear Fresnel, power tower (heliostat) and dish-sterling. A review of these designs is available in Barlev et al. [28]. Parabolic trough is the most mature technology and is being used in a number of operating power plants around the world including Andasol 1–3 in Spain (three 50 MW power plants) and the 250 MW Solana Generating Station in Arizona. An example of parabolic trough technology is shown in Fig. 2.4. In this image, the thermal receiver is supported above the concentrating mirrors. The receiver is a

Fig. 2.4 Parabolic trough concentrating solar collectors with heat transfer fluid in the tubing absorbing thermal energy (http://energy.gov/eere/renewables/solar)

black pipe encased in a vacuum tube to reduce convective losses. A high temperature, high pressure heat transfer fluid (HTF) circulates through the receiver pipes. Depending on the design of the system, the HTF fluid may serve as the heat source in an evaporator, creating steam which powers a stream turbine which drives a generator, or the HTF may directly vaporize as it passes through the solar field and then pass straight through the turbine without an intermediate heat exchanger (known as Direct Steam Generation—DSG). In either design, during periods of high insolation, it is possible to absorb more solar thermal energy into the HTF than is necessary to power the turbine. This “excess” solar thermal energy can be stored using sensible or latent heat in storage tanks as shown in Fig. 4.2.

Thermal energy storage in CSP plants has been studied by Denholm and Mehos [29] who looked at the load shifting possible by storing solar thermal energy. They point out that load shifting is beneficial both in terms of production of energy during off-peak solar periods, and in the ability to improve system flexibility by reducing constraints of ramping and minimum generation levels. Ramping and minimum generation levels are related to the need for conventional fossil-fuel powered systems to ramp up rapidly to address the decreased solar output during peak evening. In order to meet this ramp rate, it is common to operate the fossil fuel systems at part-load even during periods of solar high output. However if stored thermal energy can be dispatched to meet the peak demand in the early evening instead, the need for auxiliary systems will be minimized [29] (Fig. 2.5).

Sioshani and Denholm [30] also considered the economic impact of TES on CSP plants, particularly in the southwestern United States. In this case they examined the load shifting capability of TES systems in the context of shifting generating capability to peak electricity cost periods, thus maximizing profit. Their analysis of some Texas locations indicated that due to the matching of peak insolation time with local electricity demand patterns that CSP alone is between 7 and 35 % more valuable than the average price of electricity in the region and that adding TES increases this value by another 7–16 %. This economic benefit comes from the load matching allowing for a large solar collection field and from the higher sale prices from load shifting. From these in-depth studies it is clear that that additional of thermal energy storage to CSP plants makes economic sense.

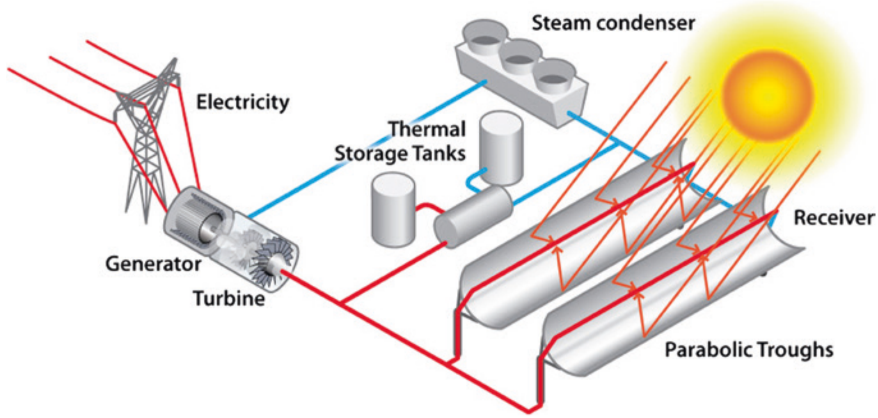


Fig. 2.5 An example of a direct steam generation concentrating solar power plant with thermal energy storage

In fact, most operational plants, including Andasol and Solana have thermal energy storage capability. Andasol has 7.5 h of thermal storage capacity while Solana has 6 h. Both of these plants use what is known as the two-tank molten salt system. In the two-tank molten system a heat exchanger is located between the two tanks with the HTF flowing on one side of the exchanger and the storage medium (molten salt) on the other side. During the energy storage cycle, some of the HTF from the solar is diverted to this exchanger where it transfers energy to the molten salt. In this case, the salt flow originates in the “cold” tank and flows through the heat exchanger where it absorbs solar thermal energy and then into the “hot” tank where it is stored [31]. During the energy discharge cycle, the HTF and molten salt flow paths are reversed. The salt gives up its energy to the HTF as it moves from the hot tank through the heat exchanger into the cold tank, and the now hot HTF is used in the power cycle. While these systems have seen success, there is significant cost inherent in using two storage tanks, and the energy density of these storage systems is low as the salt remains in the liquid phase at all times. The use of PCMs in these applications can thus reduce tank number (to one), size and installation costs, creating an economic benefit.

Molten salts are commonly used in these applications because of their high operating points. These materials have melting points from around 300 °C to over 800 °C. The HTF in parabolic trough and linear Fresnel system can reach around 300–400 °C in the receiver, while heliostats receivers can operate in excess of 2000 °C [28]. Salts are well suited for these operational ranges, but suffer from a few drawbacks including high corrosiveness and low thermal conductivity. The primary issue with low thermal conductivity is the need for quick charge and discharge of energy as the HTF flows through the storage medium. In a few cases, liquid metal alloys may be used instead of molten salts. Adinberg et al. [32] used a

70 wt% Zinc/30 wt% Tin alloy at TES temperature of 370 °C. The alloy exhibited high chemical stability and thermal conductivity of 50 W/m-K in the liquid state, an increase of about two orders of magnitude over molten salts. Both molten salts and liquid metals are discussed in more depth in Chap. 3.

An economic analysis of PCM thermal energy storage for CSP applications was completed by Robak et al. [33]. In this work they compared the costs and performance of the standard two-tank sensible heat storage model to a PCM system. In this case, the low thermal conductivity of the PCM was offset by using thermosyphons (gravity heat heat pipes) embedded within the PCM to promote heat penetration. The analytical model developed for the PCM system showed that for 9 h of storage for a 50 MW generating plant, the TES tank must be 17,464 m^3 with 30,000 tons of PCM and 3,300,000 thermosyphons. In comparison, the sensible heating system requires two tanks, each 23,856 m^3 with 45,000 tons of molten salt. Thus the PCM TES system reduces the required overall tank volume by approximately 65 %, and reduces the TES medium mass by approximately 30 % [33]. The PCM system has additional costs for the thermosyphons, and the HTF channels within the tank but the sensible heat system requires a molten salt-HTF heat exchanger and molten salt pumps. The authors estimate that overall the PCM TES system will cost 15 % less than the two tank system.

A detailed economic analysis of the benefits of PCM in CSP applications was also undertaken by Nithyanandam and Pitchumani [34]. In this analytical study they used the Levelized Cost of Electricity (LCE) metric to compare CSP plants operating on either Rankine or s-CO_2 cycles with integrated TES. Three different TES methods were considered—the standard two tank sensible heat system, PCM with embedded heat pipes, and encapsulated PCM in which the tank is filled with spherical capsules containing PCM. The PCM used in the Rankine cycle system was 60 % $NaNO_3$/40 % KNO_3, known as solar salt while the PCM used with the s-CO_2 power cycle was KCl/$MgCl_2$.

The total cost of the encapsulated PCM storage system was calculated as the sum of the costs for the HTF, PCM, container, encapsulation, and overhead costs consisting of 10 % of the storage material, container and encapsulation costs. The total cost of the heat pipe PCM system was calculated the same, with the heat pipe cost replacing the encapsulation cost. Using this cost estimation plus known data on the costs of two-tank systems, the lowest cost was shown to occur with the encapsulated PCM for both the s-CO_2 and the Rankine cycle systems. For the s-CO_2 cycle system, with no TES the LCE was 11.07 ₵/kWh, with sensible heat storage it was 6.49 ₵/kWh, with the heat pipes based system it was 5.77 ₵/kWh and it was only 5.37 ₵/kWh for the encapsulated PCM, a reduction of 48 % from the no-TES case and a reduction of 11 % over the sensible heat storage case. Similar reductions in costs were seen for the Rankine cycle systems [34].

It can be seen from this brief overview that the storage of thermal energy has been shown to be necessary in the implementation of large scale concentrating solar plants. Although the existing CSP plants use sensible heat storage with a two tank system, it is clearly shown that the use of PCM can lead to significantly lower capital and operating costs. The typical PCMs used in these applications are inorganic salts which melt in the range from 300–800 °C. These PCMs tend to be corrosive and have low thermal conductivities but it was shown that this can be offset with the use of embedded heat pipes or thermosyphons. In certain applications liquid metals may be used instead.

2.4.2 Domestic Solar Applications

While the large CSP plants certainly have significant technical and economic incentives to implement PCM thermal energy storage systems, smaller scale solar systems can also reap some benefits from TES. For example, solar thermal systems can be used by small businesses and homes for hot water production and for heating systems. A small scale solar hot water system with energy storage can be seen in Fig. 2.6. These systems feature a flat plate solar collector, typically mounted on the roof, which features a heat transfer fluid passing through the receiver tubes. The receiver tubes are isolated within an enclosure with a glass cover plate. The enclosure may be evacuated to prevent convective losses. In many ways this is similar to the CSP solar field, but without the concentrators. The lack of concentrators means that the HTF will not reach the high temperatures characteristic of CSP. As such the fluid can't be used to create vapor and drive a power system, but is hot enough to provide the heat source for a domestic hot water tank. As with CSP, the effectiveness of the system is limited to daylight hours, but the solar thermal system can be designed to store extra heat using PCM in the storage tanks for the overnight hours, greatly reducing dependence on supplemental

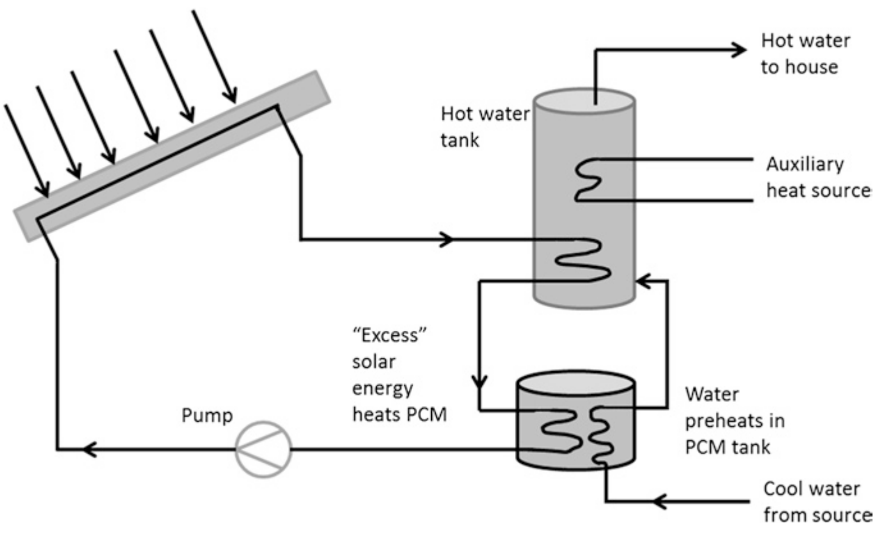


Fig. 2.6 Domestic solar hot water heating system with PCM thermal storage

natural gas or electrical heating. For instance, Sole et al. [35] designed a domestic hot water tank with a coiled heat exchanger filled with PCM in the top third of a thermally stratified tank. The PCM selected had a melt temperature of 58 °C and was a PCM–graphite compound of about 90 vol% sodium acetate trihydrate and 10 vol% graphite. The mass of PCM in this case was only 4.9 kg, compared to the 287 kg of water in the tank. The PCM tank stored approximately 3 % more energy than a comparable water only tank, proportional to the extra energy which could be stored in the PCM mass. An exergy analysis showed the PCM tank has an exergetic efficiency of 95 %, compared to 85 % for the water tank, illustrating that the energy stored in the PCM tank was of higher useful quality. Several other applications of PCM thermal energy storage in combination with solar thermal heating systems for residential and university buildings are presented in a review by Kenisarin and Mahkamov [36].

Thermal energy storage can also be used with solar thermal systems intended to heat air (instead of water) in order to eliminate or reduce the size of HVAC systems. This is particularly useful for solar heating in greenhouse systems. For example, a 180 m^2 greenhouse facility with 27 m^2 of flat plate solar air collectors [37] used 6000 kg of paraffin wax with a melt range of 48–60 °C as the medium for solar energy storage. A steel tank 1.7 m in diameter and 5.2 m long served as the latent heat storage unit (LHS). While the system was shown to be effective and energy efficient, an exergy analysis found a low net exergetic efficiency, highlighting an issue with the quality and usefulness of the stored heat in this case.

PCM thermal energy storage can also be implemented as part of a solar-aided heat pump system to allow operation during the night and on cloudy days [38]. During times in which solar insolation occurs, the thermal energy is transferred to and stored in the PCM tank and when space heating demands occur they are met using the tank's stored energy. In this application, a parametric analysis was completed to determine the effect of PCM choice on the solar energy storage time. The PCMs considered were calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) with a melt temperature of 29 °C, paraffin with a melt temperature of 47 °C and sodium sulphate decahydrate ($Na_2SO_4 \cdot 10H_2O$) with a melt point of 39 °C. The lower melt point materials melted more quickly, resulting in a faster charge of the system, but that was offset by a lower quality of the stored heat at the lower temperature. A similar system was experimentally tested for a flat plate solar collector powered heat pump system which was used to heat a 75 m^2 laboratory building. $CaCl_2 \cdot 6H_2O$ served as the energy storage medium [39]. At the installed location in Trabzon, Turkey, the stored energy met 60 % of the heating load in March, 100 % in April and provided a surplus in May.

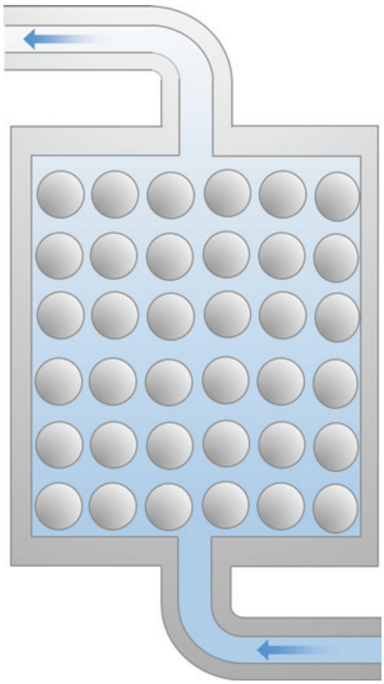
Of course, if PCM thermal energy storage units are useful for solar assisted heat pump heating systems, then they are also going to be effective with ground-source heat pump heating systems. This was shown in practice using a ground source heat pump with thermal storage in $CaCl_2 \cdot 6H_2O$ to provide heating for a 30 m^2 glass greenhouse [40]. Testing over a period from October to May, it was found that the heat pump produced a temperature increase of 5–10 °C, and the latent heat storage provided an additional 1–3 °C of auxiliary heating.

This overview of smaller industrial and domestic thermal energy storage applications shows that although the economic benefits are reduced when compared to large CSP plants, there is still a role for thermal energy storage in smaller domestic scale solar thermal heating systems. The lower temperatures for these solar applications (50–120 °C) necessitate a different choice of PCM. The typical PCMs used in these applications melted in the range from 29–55 °C and commonly included $CaCl_2 \cdot 6H_2O$ and paraffin wax. These PCMs have been shown to be effective when used with domestic solar hot water, solar assisted heat pumps and ground source heat pump systems.

2.5 Packed Bed Designs

Both large scale and domestic scale solar systems are typically arranged such that the energy storage is implemented using PCMs contained within industrial tanks of various sizes. Although the use of heat pipes to transfer and extract stored energy from the tanks was discussed in Sect. 2.4.1, in many other cases these tanks are arranged in packed bed designs. Packed bed designs typically feature large spherical capsules containing PCM closely packed within the tank. The heat transfer fluid flows in, around and over the spheres as it passes through the tank, as seen in Fig. 2.7. In charging flow, a hot fluid will pass through the tank, exchanging heat with each sphere, which contains PCM in the solid phase. The

Fig. 2.7 Packed bed design with PCM spherical capsules



energy exchange through the capsule shell leads to melting within and energy storage within the capsule. For energy discharge flow, the direction of flow is reversed within the tank. Cold fluid now flows through the tank, which warms as it passes over the hot capsules which contain liquid phase PCM. Heat is exchanged from the hot capsule to the colder fluid and the PCM transitions to solid phase as it exchanges energy. Advantages to packed bed systems include the high heat exchange contact area, and the ability to exchange energy in both charging and discharge flow in one single tank, significantly reducing costs over the two tank design. The containment of the PCM within the spherical capsules also leads to simple and reliable implementation of the system.

Packed beds designs have been around for decades, but in most cases the paced bed material does not change phase, featuring only sensible heat storage. The solid material in these designs is a a material with a high specific heat, which can store a significant amount of energy through increases in temperature. Common sensible heat packed bed storage materials include concrete, rocks and masonry. If PCMs are used instead of sensible heat storage material, smaller volumes are required to store the same amount of energy through latent heat, thus reducing capital equipment costs.

The influence of the specific heat and latent heat on the thermal response of a packed bed system was investigated by Arkar and Medved [41]. The packed bed in this study was a 1.53 m tall tank with a diameter of 0.34 m filled with 35 rows of 50 mm diameter spheres packed in a rhombic arrangement, creating a system with an average porosity of 0.388. Each sphere had a wall thickness of 1 mm and was filled with a paraffin based PCM. Both experimental and numerical models of this system were completed. It was found that the rate at which energy charges or discharges from the system is primarily dependent on the specific and latent heat of the selected PCM, and that the rate of flow of heat transfer fluid through the packed bed has a smaller influence on the thermal performance. Thus the PCM utilized must be chosen carefully to ensure the best results for a given application.

The effect of the convection rate on the outside of the capsule was quantified by Lee et al. [42] who used several different numerical models validated against experiments. The three models all used a unit cell approach to the packed bed design as seen in Fig. 2.8 The boundary conditions were applied differently in each case, with the first case using a constant temperature boundary at the edge of the PCM, the second a constant temperature boundary at the outer capsule edge to include the influence of the shell material on the thermal performance while the third used a convection boundary condition on the shell outer edge, which is most similar to the actual experimental conditions. The results showed that the inclusion of both convection and conduction through the capsule wall slowed down the thermal response of the system. The melting process was 14 % slower for this case when compared to the isothermal boundary condition at the PCM edge. The third model matched the experiments most closely, and showed that as the melting process is slowed, the thermal response of the system is affected by the PCM material choice, but also to a lesser degree by the capsule material and convection rate.

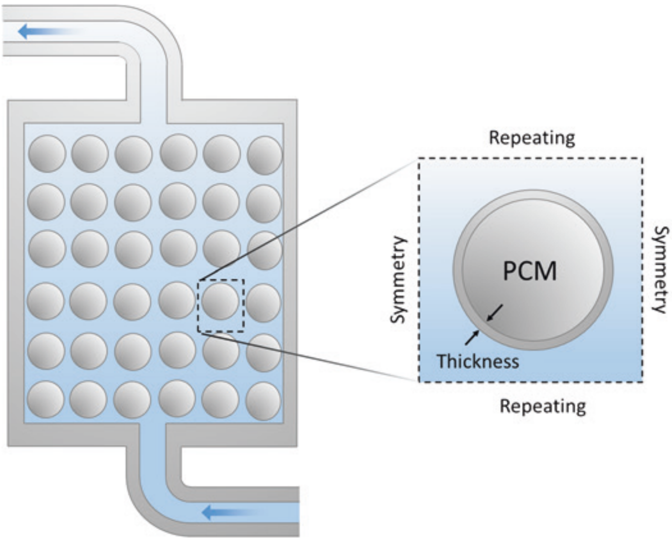


Fig. 2.8 Packed bed numerical analysis unit cell

As the PCM material properties were found to have the greatest effect on packed bed thermal performance, several other researchers focused on the effect of various thermal property enhancements on packed bed designs, including the effect of dispersing high conductivity particles within the PCM capsule [43]. This study developed a numerical model that assessed the impact of macroscale high thermal conductivity inclusions within the PCM on the energy charge and discharge rates. The thermal conductivity changes were modeled using an effective thermal conductivity model for the composite material which was a function of the particle conductivity, PCM conductivity and the particle volume fraction.

The packed bed was modeled in discharge flow during which the PCM slowly solidified as dissipated heat into the fluid flowing through the bed. The high conductivity particles were not found to exert much influence on the initial stage of discharge during which the superheated liquid PCM approached the solidification point. Once solidification began however, and the energy transfer became conduction dominated, the particles exerted a strong influence on energy discharge. The addition of the particles to PCM resulted in quicker energy discharge, leading to a faster warming of the heat transfer fluid and a faster solidification rate of the PCM. This increased energy transfer rate continued throughout the solidification process and also through the supercooling of the solid PCM. As the supercooling process is completely conduction based, increases in thermal conductivity are particularly significant.

The particle fraction was found to affect the rate of energy discharge with higher particle fractions leading to faster solidification of the PCM. Particle fractions of 10, 20 and 30 % decreased the solidification time by 8.7, 17.5 and 26.2 % respectively.

The effect of particle conductivity was less significant than the particle fraction. Increases in conductivity ratio of particle to PCM ($k_{particle}/k_{PCM}$) from 1 to 10 were found to be significant, but further increases from 10 to 50 had much lower effects on discharge rate. Thus the type of particle chosen is less significant than the loading fraction.

This overview of packed beds with thermal energy storage shows that the use of packed beds offers significant benefits in the application of PCMs for energy storage. The systems are simple to install and offer a lot of surface area which can lead to enhanced heat transfer to the operating fluid. Ongoing work on optimizing the performance of packed beds shows that the choice of PCM has the strongest influence on the charging and discharging rates. While PCMs for packed beds should be selected primarily for appropriate melt temperature range, improvements in thermal properties using high conductivity inclusions can improve thermal performance. The rate of flow through the packed bed was found to exert a lower influence on overall system performance.

2.6 Heat Exchanger Designs

The previous section illustrated the possible benefits of PCM thermal energy storage in commercial and domestic scale solar systems. In many of these systems, the PCM is implemented in a heat exchanger type design where the heat from the solar field is used to charge the storage tank. In fact, PCM energy storage heat exchangers can be useful in any system in which an excess heat capacity can be stored for future use through heat exchange from a process fluid into a PCM storage system.

These designs often take the form of a shell and tube heat exchanger system with the PCM on the shell side as seen in Fig. 2.9, although some designs have the PCM on the tube side. The choice of PCM material in these applications will depend on the operating temperature range of the system and can include molten salts for high temperature waste heat recovery and paraffin for lower temperature domestic heating systems.

Here we will present some of the design and application issues involved with using PCMs in heat exchangers. There have been numerous studies of PCM in heat exchanger designs, and there are a couple of comprehensive reviews available. Jegadheeswaran and Pohekar [44] review a number of shell and tube designs within the context of a larger review of PCM melting, solidification and heat

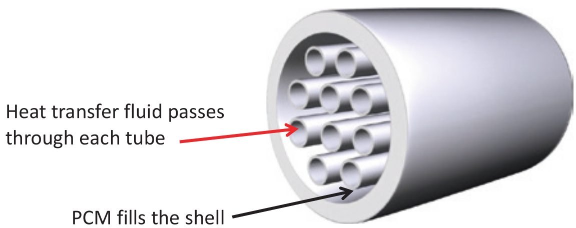


Fig. 2.9 PCM on the shell side of a shell and tube heat exchanger

transfer enhancement methods and Al-Abibi et al. [45] include a section on PCM usage in heat exchangers within the context of a review of thermal energy storage in HVAC systems.

The effective application of PCM in a shell and tube exchanger for thermal energy storage requires a low thermal resistance between the heat transfer fluid in the tubes and the PCM in the shell. When operating in charging flow, with hot HTF acting to melt the shell side PCM, it is desirable to transfer as much heat as possible as the fluid flows through the tubes. In this case, with melting PCM, the heat transfer will be convection dominant on the outside of the tubes, as natural convection is induced in the shell side. When operating in discharge flow, with the heat extracted from the molten PCM, the heat transfer will be conduction dominant as the PCM solidifies around each tube. Much of the design work in this application has considered methods to reduce thermal resistance in both melting and solidification in order to most effectively transfer heat in and out of the PCM to the flowing HTF.

Various different shell and tube side modifications have been analyzed for their effects on thermal resistance. For instance, the use of longitudinally internally finned tubes has been considered as a method to induce tube-side turbulence and create a lower total thermal resistance to the shell [45]. The design was analyzed numerically during the melting/charge phase. The addition of internal tube fins was found to significantly increase the rate of PCM melting, and thus decrease charging time. The melting volume fraction, which reflects the progression of the melt at a given point in time, increased with the fin thickness, height and number of fins.

The use of high conductivity particles dispersed within the PCM has also been found to reduce thermal resistance during melting of a shell-side PCM [46]. An analytical method was developed to study the melting progression in the PCM and to determine the optimum fraction of particles for maximum energy storage. The addition of the particles in the PCM was found to reduce the thermal resistance and promote a faster charging (melting) time. However, the inclusion of the particles displaced some PCM mass. The greater the volume fraction of particles, the lower the overall energy storage. The optimal particle fraction was found to depend on the ratio of the particle to PCM thermal conductivity, the thickness of the PCM layer and the flowrate of the HTF within the tubes.

Another way to optimize the thermal response of a PCM heat exchanger during charging and discharging is to design the exchanger to contain multiple PCMs with different melting ranges. A multiple PCM exchanger for high temperature applications was analyzed by Li et al. [47]. In this design, the PCM with the highest melt temperature is located at the inlet to the exchanger and occupies the first 1/3 of the shell length, the second PCM with a lower melt temperature fills the middle third of the shell and the PCM with the lowest melt point fills the final 1/3 of the shell as shown in Fig. 2.10. In this way, as the HTF drops in temperature as it traverses the tube, the temperature difference between the HTF and the melt point of the PCM is adjusted by moving to lower melting point PCMs, maintaining a more consistent heat flux.

While the analytical studies discussed above do not consider the effect of natural convection during the melt phase, experiments have shown that in practice the

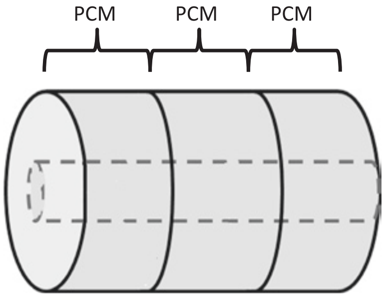


Fig. 2.10 Cascaded PCMs with different melt temperatures

density differences between the solid and liquid PCM phases do induce significant natural convection in the melt phase. This natural convection increases heat transfer for a faster melt process. Akgun et al. [48] illustrate this experimentally, and in fact show that this convective effect can be enhanced by inclining the shell 5°, which decreases the melt time by 30 %.

Since the melting phase can be shortened using the effects of natural convection, it is the solidification process that is the limiting factor in the design of PCM heat exchangers. During energy discharge, the PCM solidifies slowly on the cold tubes. The heat transfer from PCM to HTF is conduction dominated and it takes much longer to solidify the PCM than it did to melt it [49]. The energy discharge (solidification) process must be shortened for effective implementation of PCM heat exchangers. This can be done in several ways, including the use of fins or embedded high conductivity particles to improve the thermal response. A long spiral fin wrapped around the inner tube is used in a concentric tube heat exchanger by Liu et al. [50]. The fin is shown to reduce the solidification time by up to 50 %. Sanusi et al. [49] showed graphite nanofibers in paraffin PCM to be even more effective with a decrease in solidification time by over 60 %.

It can be seen from this overview that PCMs can be implemented in heat exchanger designs for quick charge and discharge of thermal energy to/from a flowing heat transfer fluid. The PCM is typically installed on the shell side of a shell and tube exchanger and the PCM used will depend on the temperature of the application. The main design concern with PCM implementation in this manner is the reduction of thermal resistance during both melting and solidification. The thermal resistance is often reduced by the use of both internal and external fins on the tubes, and by the use of high conductivity particles in the PCM itself.

2.7 Textile Designs

A relatively new, but extremely interesting, application of PCMs is in the design of clothing that enhances comfort in extreme hot or cold conditions. In many ways, this application is similar to the use of PCMs in building materials for maintenance of comfortable environmental conditions, but with the implementation of

PCMs in textiles rather than in concrete or wallboard. This can allow the design of portable personal environmental control systems for both indoor and outdoor use. By embedding PCMs within various textiles, both clothing and accessories with thermal management capabilities can be designed. A handful of products have been or are commercially available and include thermally regulating parkas, vests, snow pants, underwear, socks, sleeping bags, blankets, duvets, mattresses and pillowcases [51].

For hot weather gear, these products are designed to absorb excess heat from the environment, thermally isolating the human body from excess temperatures. In extreme climates, the heat is absorbed directly into the PCM which then maintains a comfortable microclimate next to the body as the PCM melts. The goal, similar to that previously examined for thermal management of electronics, is to delay the onset of steady-state temperatures as along as possible by matching the melt time of the PCM material to the time of exposure to the high temperatures. Once completely melted, the liquid PCM will rise in temperature until it reaches steady-state, and must be cooled and solidified before its next use. If the useful melt time can be extended to several hours, these types of garments can be extremely effective. In fact, the US military has shown significant interest in PCM textiles designs over the years, funding multiple studies on gear design for use by troops deployed to extreme environments. This type of system can also be effective in sports and exercise gear.

For cold weather gear, the idea is similar but with the heat source reversed. In this case, the PCM absorbs heat from the human body and as it melts, isolates the body from extreme cold. The longer that the PCM can be maintained in melt phase as it absorbs heat from the body, the longer the gear remains effective. This can be particularly useful in certain types of parkas, including ski gear. As the user exercises outdoors in cold weather the heat generated by the activity level is absorbed into the melting of the PCM. During periodic rest breaks, such as on a ski lift, the PCM begins to solidify, but maintains a constant temperature at the melt point, increasing comfort levels for the user in comparison to normal gear which cools down quickly when the user is at rest.

For textile based applications such as these, PCMs with melt temperatures from 12 to 35 °C will be most effective. Melt temperatures for cold weather gear should be at the lower end of this range in order to ensure that melting is induced from the body heat and activity levels. Even a 12 °C melt point can enhance user comfort in outdoor winter environments of 0 °C and lower. Higher melt temperatures should be selected for warm weather apparel to increase the length of the melt process by minimizing the temperature differential between the environment and the melt temperature. The various types of paraffin waxes are popular for textiles applications due to their suitable melt temperature ranges, their high latent heat and their nontoxic, chemically inert nature [51]. Paraffin can be incorporated into the textiles in several different ways including the insertion of PCM-containing packets in the design of the garment, in the application of coatings containing microencapsulated PCMs to the fabric, or in the direct incorporation of the PCM into the fibers themselves.

The simplest, although perhaps least comfortable, method of incorporating PCMS into garments is through the use of macroscale encapsulation of PCM in flexible packs inserted into pockets in the garment itself. In one application, blister packs containing PCM were created which featured multiple cavities 10 mm in diameter and 4 mm deep sealed with foil. The material was then used to line protective clothing for workers exposed at regular intervals to the heat from industrial ovens [52]. Samples were made using four different PCMs in the blister packs and the gear was tested in exposure to a 1500 W/m^2 radiation heat flux at a distance of 50 cm. The testing occurred over three phases. In phase one the sample was protected from direct irradiation by a fireclay for two minutes. The fireclay was then removed and the sample exposed to direct irradiation for 10 min. In the final phase the fireclay was replaced for an additional 15 min of exposure time. All of the samples reached 120 °C on the front face of the gear by the end of 10 min of direct irradiation, but the PCM blister packs reduced the rate of temperature rise on the rear of the sample, corresponding to the human-clothing interface, indicating significant comfort improvements. The best design reached only 75 °C on the rear side after a full 10 min of direct exposure, a reduction of 37 % in operating temperature.

Although effective for high heat flux exposure, for more moderate environments the use of large PCM lining packs is unnecessarily heavy and bulky. Instead, the PCM can be contained within microscale polymer beads, and coated onto the fabric as shown in Fig. 2.11. For instance, a fabric made by the Outlast company and referred to as "Outlast/silk" composed of 57 % Outlast viscose (weft yarn, 50 s) and 43 % silk (warp yarn, 22D) was coated with a mixture of 15 wt% microencapsulated PCM, 15 wt% polyurethane binder and thickener (12 g/l) [53]. Thermal testing of the prepared fabrics showed that the microcapsules evenly coated the fabric without affecting the airflow through the fabric, which is important for breathability and comfort of the garments. The fabric coated with the PCM capsules exhibited an energy storage capability of 7.71 J/g, a 95 % increase over the base fabric [53].

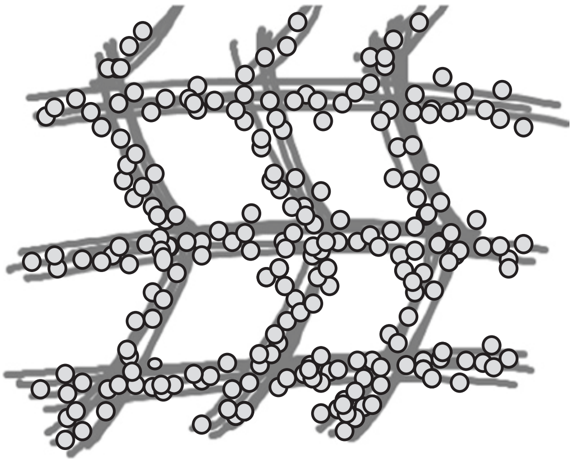


Fig. 2.11 Fabric coated with microbeads of PCM

A study of the effectiveness of microencapsulated PCM coated fabric using a human-clothing environment simulator (HCE) was completed by Yoo et al. [54] for cotton coated with 8–30 μm microcapsules beads containing nonadecane PCM with a melt temperature of 29 °C. The fabric was treated with the prepared microcapsules in an acrylic binder [54]. The materials were tested under exposure to a hot temperature source of 34 °C and a low temperature condition of 10 °C. Sample garments were comprised of four layers of material which varied parametrically with the number and location of PCM treated layers. The PCM coated material was shown to both reduce temperature rise when exposed to the hot conditions and to reduce heat loss when exposed to cold conditions. The more layers coated with PCM, the greater the thermal control effects within the garment [54]. The possible disadvantages to coating treatments are concerns about fabric stiffness and about the long term durability of the coating during repeated washings.

To eliminate the concerns with coating durability, fabrics can also be created by incorporation of the PCM directly into the fibers themselves. For example, fibers can be fabricated using a co-axial electrospinning technique which creates a hollow fiber with PCM in the central core, such as those fabricated by Chen et al. [55] with a cellulose acetate shell and a polyethylene PCM core. The fibers were extruded using a stainless steel needle with an outer diameter of 0.9 mm and an inner diameter of 0.6 mm. Thermal testing of the fibers showed good stability over repeated cycling, and latent heat storage of 52–60 J/g during melting depending on the exact composition of the fibers. However, the incorporation of the PCM into the fiber sheath reduced the overall tensile strength of the fibers, which must be considered in the application of the material. While this technique is still under development, and few if any applications currently exist, the potential for the technology seems high.

It can be seen from this overview that PCMs can be effective in moderating environmental temperature effects when embedded in textiles for use in apparel and accessories design. The PCMs can be embedded by macroencapsulation in large packs, by fabric coating with microencapsulated spheres and by direct containment within the fiber sheath. The PCM melt temperature range should be within 11–35 °C and several commercial products are currently available. The barriers to greater adoption seem to be comfort and durability issues, as well as cost for the more complicated fabrication techniques.

2.8 Space Systems

The use of PCMs in space systems is one of the oldest and most enduring applications of these materials. The excessive temperature swings inherent in most space applications demand a high level of thermal control and the passive and reliable behavior of PCMs makes them a natural fit for these systems. In many early space systems, PCMs were used to maintain a consistent temperature over time, and for this reason NASA referred to their PCM designs as thermal capacitors. In many

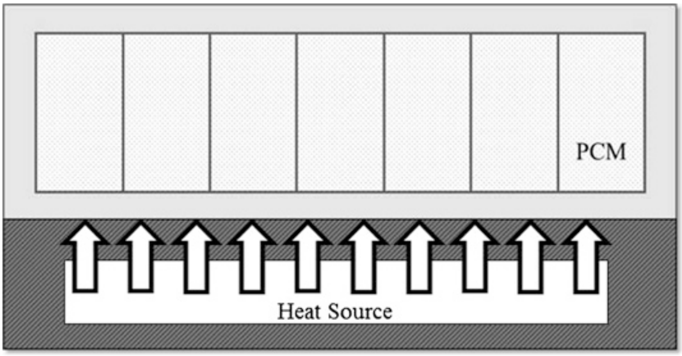


Fig. 2.12 A thermal capacitor device

NASA applications the "thermal capacitors" were comprised of an external housing, and a finned inner area filled with a PCM as seen in Fig. 2.12 [1].

Thermal capacitors of this type, using paraffin as the PCM, were used on Apollo 15, 16 and 17 for thermal control of various electronic components on the Lunar Rovers [1]. Even more were used in the design of Skylab, the original manned space station. Five were located in cooling systems, with two of these on the primary Skylab space radiator fluid outlet, and three at the outlet of a smaller radiator used to refrigerate food and biological waste samples. Ten other thermal capacitors were mounted in the bottom of trays used to store human urine samples [1] during transport from the Skylab Vehicle to earth, perhaps not the most glamorous application, but certainly functional.

The 1977 NASA tech brief "A Design Handbook for Phase Change Thermal Control and Energy Storage Devices" [2] was one of the first comprehensive PCM references, and with its property database and basic design guidelines, it is still widely cited and used today. The use of PCM in the 0-g environment of space does lead to certain design issues that do not occur in normal terrestrial applications. The most serious design issue is the complete elimination of the buoyancy forces which create natural convection in the melt phase. In the absence of standard natural convection, Marangoni convection, which is driven by surface tension forces, can play a more significant role in heat dissipation [2]. However, the overall melting rates will be reduced. Additionally the volume contraction of the PCM which occurs during solidification occurs slightly differently in space. In earth gravity, when the PCM solidifies and contracts it always leaves an empty space at the top of the system. However, in 0-g the location of the void is not at the top of the container. Instead the void may change location, may be distributed as a number of smaller voids throughout the system or may occur at the very center of the PCM mass [1].

In 2003, a review of thermal control solutions for contemporary space applications was published by Swanson and Birur [56]. In this paper a number of systems are reviewed, and PCM is identified as the solution of choice for several systems including the Mars rovers, Spirit and Opportunity, which were launched in 2003.

In these systems, paraffin waxes, dodecane and hexadecane, were used in thermal storage capsules to control battery temperature and damp out temperature fluctuations. Interestingly, this paper also describes the development of a PCM actuated thermal switch in which the volume change of the wax under heating or cooling would make or break a contact actuated switch that prevents warm objects from getting too cold, or cold devices from getting too warm in extreme environments.

In an application somewhat similar to the human urine transport from Skylab, PCM is currently being used for thermal stabilization of biological samples, such as cell samples, used in scientific testing aboard the International Space Station (ISS) during transport to and from the earth. PCM based sample containers were developed by the European Space Agency (ESA) and are referred to as ECCOs (ESA Conditioned Containers). The ECCOs utilize containers of two different sizes matched with modular PCM cartridges with different melt points depending on the application. The thermal control points available include below −20 °C, from 2–10 °C or above 23 °C [57]. The different container sizes allow transport on the Space Shuttle, Soyuz, Progress (an older Russian transport vehicle), ATV (the EAS vehicle) and HTV (Japanese transport vehicle), and is compatible with the new SpaceX dragon vehicle. Another smaller container (Mini-ECCO) can be transported in the Soyuz crew re-entry capsule. In operation, the containers are “pre-charged” by fully solidifying the PCM prior to launch so that the PCM melts slowly from supercooled conditions through trip, maintain the desired temperature. These transport containers have been used successfully since 2008 [57].

In the reverse of this application, premelted PCM is used to provide heat to systems onboard launch vehicles during the trip from earth to the ISS [58, 59]. While in most cases, the transport vehicle can provide heating power during the actual trip, during the time that it takes for payload transition at the ISS, the transport vehicle can be unpowered for as long as 6 h. This extensive length of time without heat in space can lead to the payload temperature falling below the electronics cold survival limit of −30 °C. By melting the PCM prior to power cutoff, enough energy can be stored for release into the payload to keep it warm for several hours [58].

Choi [59] applied this concept model to the design of a particular application, the transport of the Neutron Star Interior Composition Explorer (NICER) in the SpaceX dragon transport vehicle. The payload volume of the SpaceX vehicle is 3.6 m in diameter by 2.3 m tall with the interior insulated with a 7.62 cm thick acoustic blanket [59]. NICER is an X-ray timing and spectroscopy instrument to be used to study neutron star emissions from aboard the ISS. NICER is due to be launched in Dec. 2016. NICER features a 1.18 m by 0.87 m by 0.82 m Instrument Optical Bench (IOB) with the spectroscopy instruments. The electronics to run the instruments are all mounted to a single heat spreader which is thermally isolated from the IOB.

Several paraffins were considered for use as the PCM, including dodecane, tetradecane, and tridecane. Ultimately dodecane, which features a high latent heat of fusion (217 kJ/kg) and a low melting point (−10 °C) was chosen. The proposed design features four PCM panels located between the electronics heat spreader and the IOB, each with 0.51 kg of paraffin. Six additional paraffin panels are used to wrap around the IOB, each with 0.38 kg of PCM. The 4.32 kg of dodecane will store up to 937 kJ of thermal energy as latent heat.

The model assumes that NICER is removed from the Dragon trunk at orbit noon and immediately begins cooling down. When the payload reaches −10 °C, the PCM solidifies and then will subcool after full solidification. After 6 h without power, the model predicts a final payload temperature of −13 °C, which is adequate protection from the electronics failure point of −30 °C.

As this overview illustrates, PCMs have a long and successful history in many varied space applications from vehicle electronics to sample transport. The PCMs used in these systems are most often paraffin, and feature low melt points, as low as −10 °C, to protect systems from the harsh space environment.

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